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ABSTRACT

The monitoring of nuclear explosions on a global basis requires accurate event locations. As an example, a typical size used for an on-site inspection search area is 1,000 square kilometers or approximately 17 km accuracy, assuming a circular area. This level of accuracy is a significant challenge for small events that are recorded using a sparse regional network. In such cases, the travel time of seismic energy is strongly affected by crustal and upper mantle heterogeneity and large biases can result. This can lead to large systematic errors in location and, more importantly, to invalid error bounds associated with location estimates. Calibration data and methods are being developed and integrated to correct for these biases. Our research over the last few years has shown that one of the most effective approaches to generate path corrections is the hybrid technique that combine both regionalized models with three-dimensional empirical travel-time corrections.

We implement a rigorous and comprehensive uncertainty framework for these hybrid approaches. Qualitative and quantitative validations are presented in the form of single component consistency checks, sensitivity analysis, robustness measures, outlier testing along with end-to-end testing of confidence measures. We focus on screening and validating both empirical and model based calibrations as well as the hybrid form that combines these two types of calibration. We demonstrate that the hybrid approach very effectively calibrates both travel-time and slowness attributes for seismic location in the Middle East, North Africa, and Western Eurasia (ME/NA/WE). Furthermore, it provides highly reliable uncertainty estimates. Finally, we summarize the NNSA validated data sets that have been provided to contractors in the last year.

KEY WORDS: Location, Integration, Uncertainty Framework, Validation

Objective

This paper discusses the primary focus of the Livermore seismic location effort to integrate a diverse set of three-dimensional velocity model and empirical based travel-time products (developed both in house and through external contracts) into one consistent and validated calibration set. Integrating reliable velocity models that correct for systematic travel time anomalies is critical to providing accurate and reliable estimates of seismic event location. If these anomalies are not accounted for, then the predicted errors will likely misrepresent the true uncertainty of an event's location. At Livermore, we have implemented a unified framework that combines empirical-based kriging with model-based path corrections to remove this type of bias from the location problem, as shown in Figure 1. Our framework incorporates any combination of *a priori* and *a posteriori* one-dimensional, two-dimensional, and three-dimensional models. These error distributions are then propagated into our coverage ellipse estimates. Our focus this year has been on the merging of these models geographically and on developing a validation process that can provide high *confidence* in our confidence estimates.

Research Accomplished

Much of the current university and other external research has focused on developing model-based corrections that work to improve travel-time prediction at both regional and upper-mantle triplication distances. Beyond the upper mantle distances global Earth models plus a static station correction generally provide excellent travel-time prediction. Thus, we typically merge regional and teleseismic models just beyond the upper-mantle triplication distance. In the regional distance range, we allow for the merging of an optimal combination of regional models. After a merged set of calibration velocity models are applied at a station, we add empirical corrections using the nonstationary Modified Bayesian Kriging algorithm (Schultz et al., 1998) where travel-time residuals for suitably well located calibration events exist. Since the teleseismic errors are quite small, only the highest quality reference events are useful at these larger distances. At regional distances less precise ground truth is still helpful (e.g. 20 kilometer accurate ground truth). Our approach combines the extrapolative advantages of model-based corrections and the interpolative/statistical advantages of Bayesian prediction (i.e. modified kriging) to produce hybrid travel-time predictions and uncertainty models. For ease of use, model-based and empirical corrections are combined to produce one travel-time correction and uncertainty model that is applied to the optimal global Earth model for a given station. However, any model that can be described by a depth/distance/travel-time file can be utilized in our system.

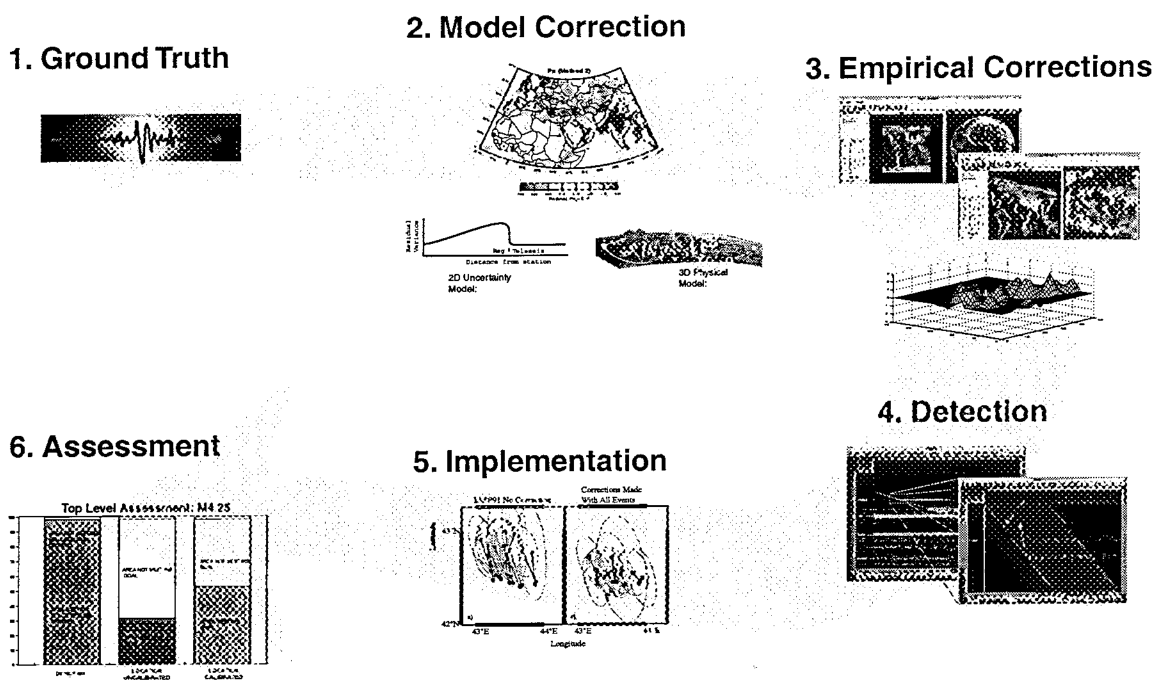

Figure 1: Developing a comprehensive framework for location.

We continue to work closely with Sandia National Laboratory to implement a framework that allows us to design, build, integrate, and visualize the calibrations that are produced by combining our own internal NNSA research with that provided through research associated with external contracts. A large part of our effort at Livermore continues to be concerned with generating standardized detection, travel-time, and amplitude correction volumes on a regional basis.

Development and Validation of 1-D, 2-D, and 3-D Models

We investigate our ability to improve seismic event location accuracy in the Middle East, Northern Africa, and Western Eurasia (MENAWE) by developing 1-D, 2-D and 3-D velocity models of the crust and upper mantle to account for velocity heterogeneity in the region. Event locations based on 1-D models are often biased, as they do not account for significant travel time variations that result from spatially heterogeneous crust and mantle structure. Previous studies have shown that event locations and uncertainties can be improved by applying empirical travel-time corrections relative to the default *iasp91* 1-D model [*e.g., Myers and Schultz*, 2000]. Empirical corrections and other model optimization methods are well suited to improve travel-time prediction in areas where GT events are available. However, vast portions of the MENAWE region are devoid of GT events, thus we seek to improve travel-time prediction at regional and near teleseismic distances in regions without GT calibration.

Our approach here is to develop model-based travel-time correction surfaces derived from several different models which can be used along with empirical travel-time residuals and Ground Truth (GT) event locations for validation and testing. We explore the degree of improvement in location accuracy and uncertainty achieved by each velocity model using a variety of validation techniques. The velocity models we tested are of three types: 2-D radially heterogeneous, station specific models derived from regressing travel times; a *Pn* velocity model produced by tomographic inversion; and an *a priori* 3-D model based on geophysical studies ranging from seismic reflection to geophysical analogy. Model-based travel-time predictions remove predictive travel-time residual trends and provide improvement relative to global models, as well as providing the requisite zero-mean distributions for kriging.

2-D Station Specific Velocity Models

In order to improve the travel-time predictions at regional and near teleseismic distances, we develop 2-dimensional, station-specific travel-time models that are optimized to predict travel times from GT events. The data used are a set of teleseismically constrained *P*-phase arrival times from a declustered dataset (described above). We use 100% of the groomed data set to compute our 2-D models. In the model validation phase, we leave 90% of the data out and use a 10% data subset to estimate the prediction uncertainty. The dataset is parsed into three distance ranges regional (1°-13°), upper-mantle (13°-30°), and teleseismic (30°-90°) based on the depths of the turning rays and therefore upon the portion of the earth sampled by the wavefield.

The first step in creating 2-D radially heterogeneous and azimuthally invariant travel-time models is to create 1-D regionalized travel-time models for each station at each of the distance ranges described above. We developed an adaptive grid search method that efficiently samples and explores the space of reasonable models, allowing the four most influential model parameters (crustal thickness, upper and lower crustal *P*-wave velocity, and upper mantle *P*-wave velocity) to vary. The eight model parameters we use to describe model space are crustal thickness, upper and lower crustal *P*-wave velocity, upper mantle velocity, sediment thickness, sediment *P*-wave velocity, thickness of the mantle lid, and *P*-wave velocity gradient in the lid. We calculate travel times through each regionalized *P*-wave velocity model using a ray-tracer that employs the single-valued *tau-p* formulation similar to that of Buland and Chapman (1983). An earth-flattening transformation is used to account for the sphericity of the earth, which preserves the kinematic properties of the rays. The resulting travel-time tables are populated with travel times, parameterized by distance and depth.

To test the predictive power of each 1-D regionalized model, we compute the mean residual and an *rms* residual between the declustered *P*-phase arrivals at each station and the arrivals predicted by each 1-D travel-time model. We repeat the calculation for the declustered *P*-phase arrivals at each station and the arrivals predicted by the *iasp91* model. When we rank the models according to *rms* residual, we find that a suite of models predict the travel-time arrivals equally well. We choose to further minimize our models against our background model (*iasp91*) to address distance discontinuities between the regionalized models and to promote a smooth transition to the background model outside the coverage area of our models.

To ensure a smooth travel-time curve, we merge our preferred 1-D regionalized curves smoothly at the distance thresholds to produce 2-D curves. Merging is accomplished using a sine-taper (smoothing) function to reduce distance discontinuities between the individual curves. The sine-taper is applied over a distance range of 1°, so that travel-times are smoothed between 12.5° and 13.5°, and between 29.5° and 30.5°. The result is a radially heterogeneous and azimuthally invariant travel-time curve for both the crust and upper mantle. When we compute travel-times through the 2-D models and compare predicted arrivals with the data, we find that our 2-D models improve travel-time fit (reduction in *rms* residual) and reduce the bias, relative to *iasp91*. Repeating the process with the 10% validation data set demonstrates that we also improve travel-time predictability with our 2-D models. Results for two representative stations are shown in Figure 2.

Pn Velocity Model

We derive a model of uppermost mantle P-wave velocities throughout the Middle East, North Africa, and Former Soviet Union using regional P-wave travel times from a groomed version of the ISC catalog (Engdahl *et al.*, 1998). This catalog was then statistically declustered spatially in order to reduce the size of the dataset and to identify and

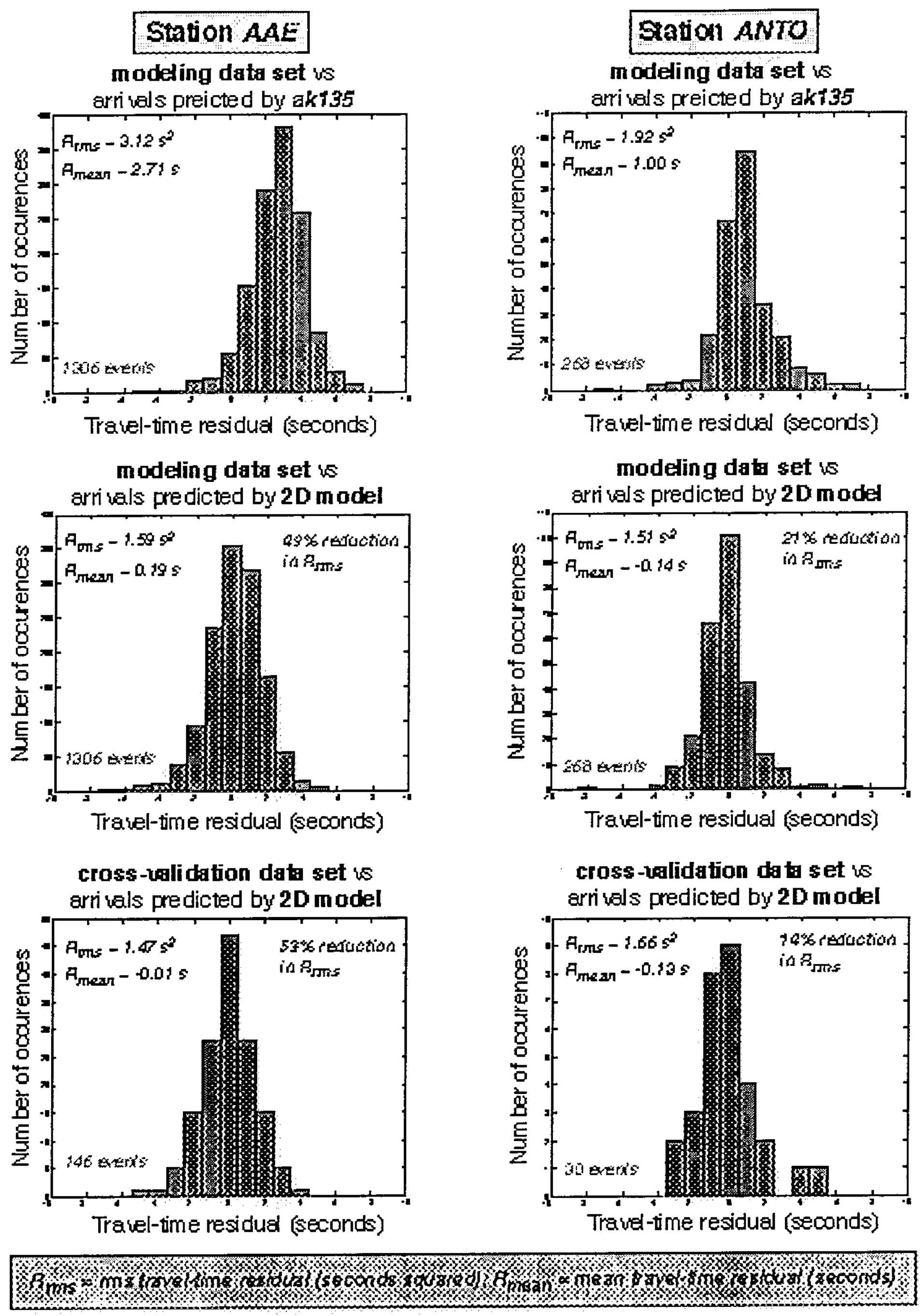

Figure 2. Histograms show the distribution of travel-time residuals at stations AAE and ANTO. Top row: travel-time residuals relative to *iasp91*, using the modeling data set. Middle row: travel-time residuals relative to our preferred 2-D model, using the modeling data set. Bottom row: travel-time residuals relative to our preferred 2-D model, using the cross-validation data set.

remove outliers. The top panel in Figure 3 shows the path coverage for the inversion. Notice the highly uneven sampling of our study area, with many raypaths in the Mediterranean, Europe, the Middle East and Indian subcontinent and few or no raypaths in Africa, the Former Soviet Union, and the oceans.

We have used a conjugate gradient method for the P-wave velocity tomography. The conjugate gradient technique is a search method that works very well on sparse linear systems like the travel time problem.

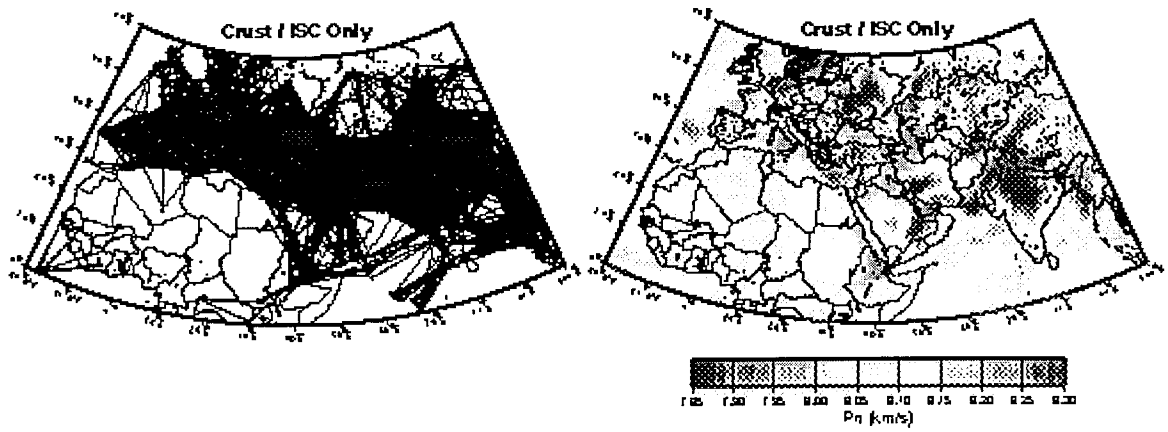

Figure 3 Paths and uppermost mantle P-wave velocites from the P_n tomography. We find slow upper mantle velocities along the Tethys collision zone and Red Sea rift, and fast upper mantle velocities in India and southern Former Soviet Union.

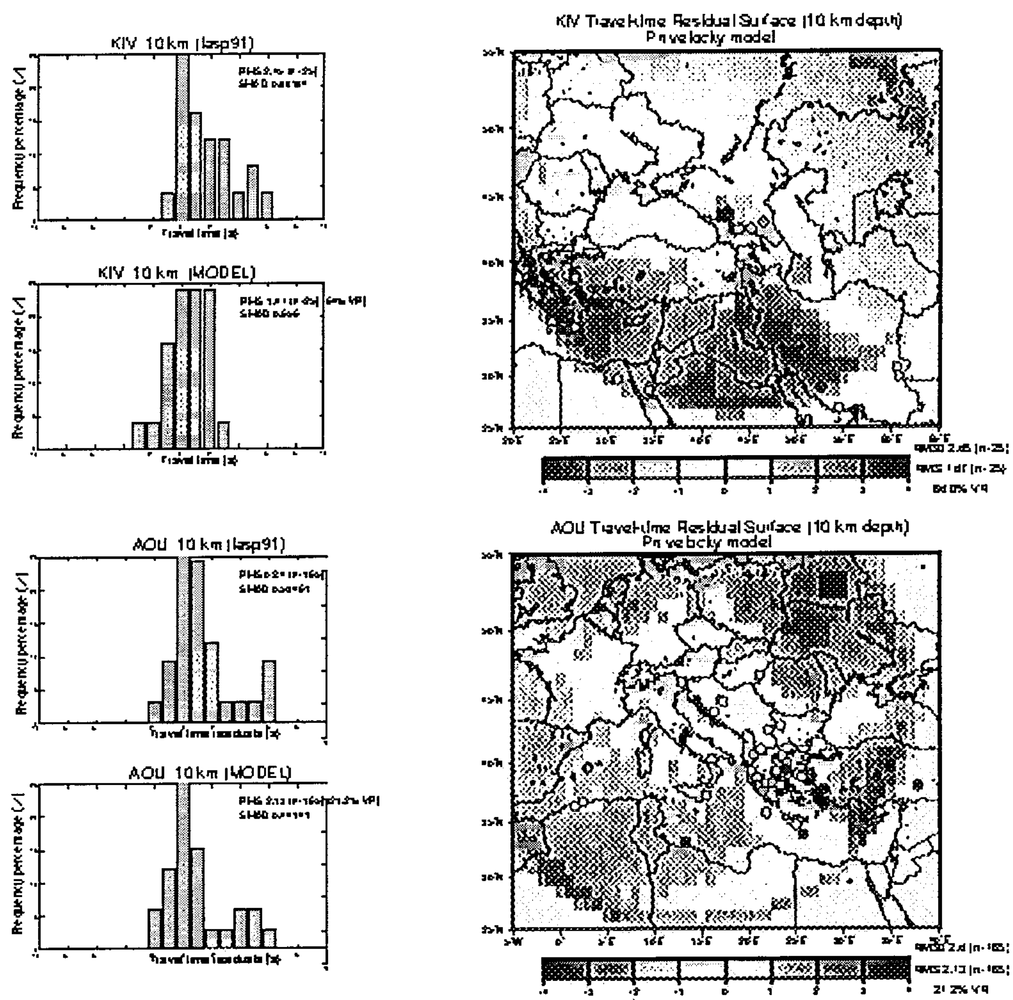

Figure 4. *P*-wave travel-time correction surfaces and histograms for stations KIV and AQU based on our *Pn* tomography model.

Because there is no matrix inversion involved, it is well-suited for large systems of equations. We chose a 2 degree by 2 degree grid for the inversion, and within each grid, we solve for the P-wave velocity in both the crust and upper mantle, assuming a crustal thickness of 35 km (Pasyanos, 2000). We currently provide uncertainty estimates for the P-wave velocities in the crust and upper mantle for the P_n tomography.

From the inversion results, we are able to provide three-dimensional background P-wave travel times correction surfaces for any seismic station. We can construct the travel times along any given path by integrating the P-wave slowness results from the tomography results. We can then build the surface by calculating the travel times along a regular grid in latitude, longitude, and depth. Travel times in the surfaces are given as residuals relative to travel times predicted by the *iasp91* model (Kennett and Engdahl, 1991) and are shown in Figure 4.

3-D a priori Velocity Model

We use MENAWE2.0 (Pasyanos, et al., 2001), a self-consistent three-dimensional Earth model for the crust and upper mantle, to compute travel-time correction surfaces for use with our location algorithm. This *a priori*, regionalized model is a preliminary set of geophysically distinct regions that can be used for estimating travel-times, surface wave dispersion, and discrimination properties particularly in aseismic regions where calibration data is sparse. The model can also provide a platform for assessing progress in seismic location, discrimination, detection—the entire calibration process—and aid in determining the priority and planning of calibration experiments. Because the MENAWE2.0 model is 3-D, region-specific velocity structure, it can be characterized more accurately than 1- or 2-D models. A representative cross-section through the velocity model is shown in Figure 5.

This *a priori* model specifies geographic boundaries and velocity structures based on geology, tectonics, and seismicity. This regionalization serves as a starting point, and we expect to refine and improve upon it based on such tests as predicting *P* and *Pn* travel times (presented here) as well as surface wave velocities. As the model improves and demonstrates some predictive power, it may evolve into a base model for tomographic inversions as well as a reference model for other CTBT-related research efforts.

To compute travel times through the MENAWE2.0 velocity model we use an algorithm originally developed by Vidale (1988) and further refined by Hole and Zelt (1995) which uses a finite difference approximation (FD) to compute first arrival travel-times through regularly gridded velocity structures. We modify the original code in two

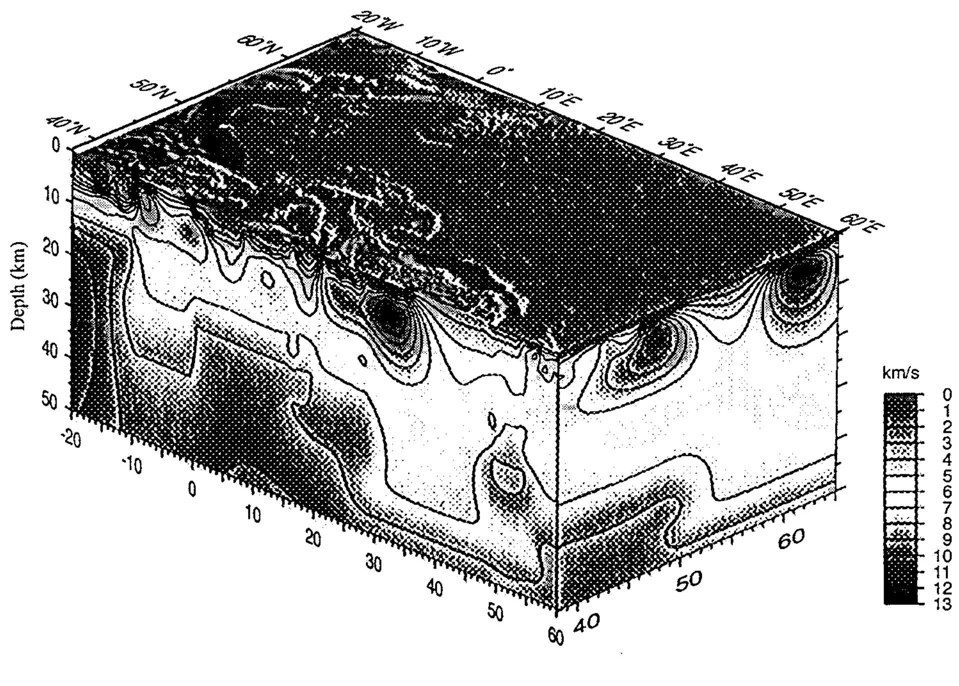

Figure 5. Cross-section of P-wave velocities from our 3-dimensional MENAWE2.0 model.

ways. First, we adapt it to read in 3-D velocity models instead of 1-D such that it can compute times through our MENAWE2.0 (or any custom 3-D) model. Second, we apply a Cartesian to spherical coordinate transformation to the source and receiver locations that are input to the code [Flanagan et al., 2001]. These modifications are necessary as we need to compute travel times out to regional and near-teleseismic distances (~13° to 30°). The code is run in a volume of dimensions of roughly 25° by 25° laterally and 800 to 1000 km deep with a grid spacing of 3 km. The grid spacing is determined empirically as a trade-off between the accuracy of the travel-time prediction and computer memory limitations, and we find that a grid spacing of 3 km provides a reasonable accuracy (i.e., timing errors of approximately 0.25 s).

We compute station-specific correction surfaces based on the P-wave travel times predicted by the FD algorithm. To compute these model-based correction surfaces we subtract the *iasp91* predicted time from the MENAWE2.0 predicted time along a regular grid in latitude, longitude and a given depth. Example surfaces at 10 km depth are shown in Figure 7 along with travel-time residuals from a groomed, declustered dataset of GT15 events (Engdahl *et al.*, 1998). We find travel time differences of up to 6 sec relative to *iasp91*, most in areas of very thick crust or sediment. Note the patterns in these correction surfaces correlate with the structural features in the MENAWE2.0 model; fast predictions are seen to the north on the Russian platform while slow anomalies are seen at the southern Caspian as well as eastern Turkey and the southern Caucasus. These correction surfaces can then be used as additional constraints in the location algorithm to improve regional seismic location.

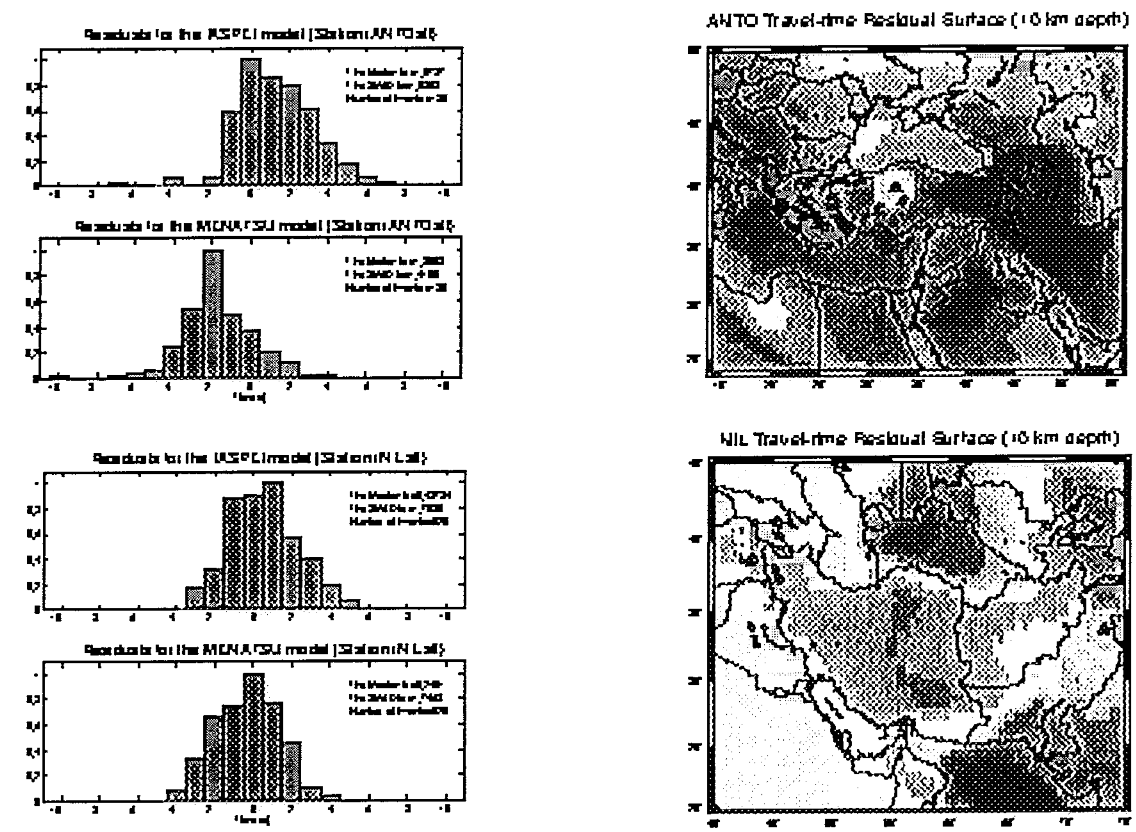

Figure 6. Example correction surfaces at 10 km depth shown along with travel time residuals from the declustered data set (blue indicates fast regions and red indicates slow). In general, travel-time variance for the MENAWE2.0 model is reduced compared to *iasp91*. In some instances the mean of the distribution is displaced from zero; however, this may be due to optimization of the event origin times relative to the *iasp91* velocity model.

To test the predictive power of the our *a priori* model we compare the travel times predicted by both our MENAWE2.0 model and the *iasp91* model with the declustered P arrivals at each station. To compute these travel time residuals we interpolate between grid nodes to calculate the predicted travel time for an exact earthquake-station path, then each predicted time is subtracted from the observed arrival time. These residuals are shown in histogram form in Figure 6. Note for some stations the 3-D MENAWE2.0 model predicts the observations very well, showing a significant variance reduction, while for others it improves the fit given by the *iasp91* only slightly.

Improving Location: The 1991 Racha Aftershock Sequence

Next we determine the improvement provided by the various models by relocating a set of ground truth events; the improvement in seismic location that is gained by using the different velocity models is the ultimate test of our approach. As a test case, we use a set of GT2 locations determined using regionally recorded aftershocks in the region of Racha, Georgia. In a previous study, Myers and Schultz (2000) demonstrated location improvement using Modified Bayesian Kriging (MBK) to compute empirical correction surfaces for a sparse 6-station test network. The MBK correction surfaces for the test-network stations are based on high-quality teleseismically constrained GT15 hypocenters throughout the Middle East (Engdahl et al., 1998). The 1991 Racha events are then relocated with and without the aid of MBK correction surfaces, and the resulting epicenters are compared to the benchmark GT2 locations determined

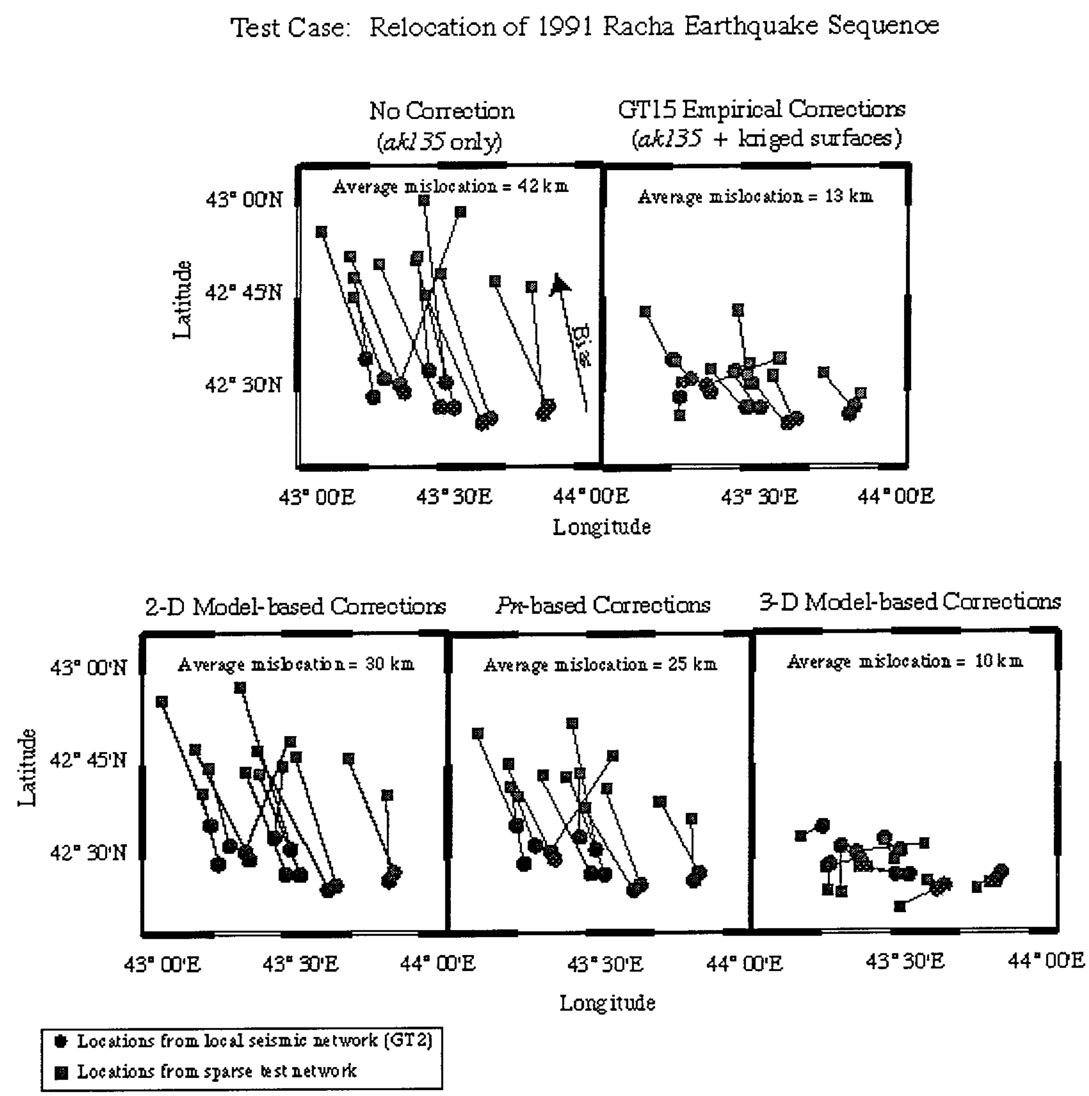

Figure 7. Relocations of the 1991 Racha earthquake sequence with correction surfaces derived from kriging empirical residuals, a 2-D velocity model, Pn tomography, and a 3-D *a priori* velocity model. Location bias is significantly reduced when either empirically derived or model-based corrections are applied to reduce travel-time prediction inaccuracies.

from a dense local deployment of seismic sensors. When no travel-time correction is applied, the mean horizontal distance between the local and test network locations is 42 km, and there is a distinct bias in sparse-network locations towards the north-northwest. The mean difference between local and sparse network locations is reduced to 13 km when the empirical corrections are applied and the bias in location is significantly reduced (Figure 7, top).

We compute model-based correction surfaces computed for the six stations (KAS, KVT, GAR, KHO, ARU, and SVE) comprising the sparse test network. We then relocate this same set of events using our model-based correction surfaces and produce an average mislocation bias of 30 km using the 2-D models, 25 km using *Pn* tomography, and only 10 km using the 3-D model. However, out of the six stations only two are regional distance from Racha, two are teleseismic, and two are very far regional distance, so the Pn correction was not always employed. This test case clearly demonstrates the power of applying model-based corrections to improve location capability for small, regionally recorded events. A larger data set of GT0-GT10 events is being collected and will be used to further evaluate the effectiveness of each model for improving event location accuracy. We are also developing a variety of validation techniques (*e.g.*, cross-validation, sensitivity tests) to model the uncertainty process for model-based corrections which will be required to compute representative error ellipses for the new locations.

Livermore Framework for Integrating and Validating Calibrations

The overall goal of our framework is to provide a flexible, interactive environment in which an analyst can produce, test, and manage calibration information for seismic stations. This framework focuses on providing accurate characterizations of location uncertainty given the highly nonstationary and regionally varying nature of seismic travel-time, azimuth, and slowness. To account for variations in regional structure, our framework is designed to account for dramatic variations in travel-times and amplitudes that occur over relatively short distances in the crust - variations that can lead to significant errors in event location.

The ability to accurately locate seismic events rests on the development of reliable uncertainty models and the careful validation of these errors at each step of the process. Figure 1 gives a general overview of the components involved in the calibration of seismic location. These components include: (1) cataloging well constrained ground truth events that can be used to assign and validate the uncertainties in the location process (Hanley and Schultz, 2000); (2) refining one-, two-, and three-dimensional velocity models to better predict travel times (Flanagan et al., 1999; Swenson and Schultz, 1999; Swenson et al., 1999; Flanagan et al., 2000); (3) applying statistical prediction techniques that work together with the travel time models to extract additional accuracy from the ground truth data (Schultz and Myers, 1998; Myers and Schultz, 1999; Myers and Schultz, 2000); (4) determining detection thresholds and filter phase filter characteristics as a function of magnitude; (5) applying state-of-the-art location algorithms; (6) assessing of our progress in improving seismic location uncertainties.

Validation and Benchmarking of Models and Empirical Surfaces

The one validation technique applied to all these modles and associated empirical surfaces is the model checking cross-validation technique. In this approach events are removed from the data set and an uncertainty model is built by differencing predicted and observed arrival times. Normalizing the difference between predicted and observed arrivals by the predicted (Bayesian Kriging) uncertainty provides validation of the empirical uncertainty model. In this case, the normalized mean, root-mean-square, and histogram are provided as validity measures.

Conclusions and Recommendations

In general, we have developed a hybrid approach to location that uses three-dimensional model corrections for a region and then uses reference events when available to improve the path correction. Our approach is to select the best *a priori* three-dimensional velocity model that is produced for a local region and then use this as a baseline correction. When multiple models are produced for a local region, uncertainties in the models will be compared against each other using ground truth data and an optimal model will be chosen. We are working towards implementing a calibration integration process of combining three-dimensional models on a region-by-region basis and integrating the uncertainties to form a global correction set. The Bayesian kriging prediction combines the optimal model combination and its statistics with the empirical calibrations to give an optimal *a posteriori* calibration estimate. The result is improved location estimates and robust location uncertainties that show significant improvement in calibrated regions (Schultz and Myers, 1999; Schultz et al., 1999).

To aid this process we have developed a general framework to provide a flexible, interactive environment in which a researcher can produce, test, and manage calibration information for seismic stations. This approach allows a general statistical analysis on a regional basis and results in a self consistent global calibration set.

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